

# Light Meson Dynamics Workshop Mini-proceedings

February 10–12, 2014 in Mainz, Germany

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## ABSTRACT

The mini-proceedings of the Light Meson Dynamics Workshop held in Mainz from February 10<sup>th</sup> to 12<sup>th</sup>, 2014, are presented.

The web page of the conference, which contains all talks, can be found at

<https://indico.cern.ch/event/287442/overview>

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# 1 Introduction to the Workshop

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The strong-interaction part of the Standard Model is described by an  $SU(3)$  gauge theory—Quantum Chromodynamics (QCD)—in terms of quarks and gluons as the fundamental dynamical degrees of freedom. However, experimentally only color-neutral combinations, namely, mesons and baryons, are observed as the asymptotic states of the theory. Unraveling the structure and dynamics of (light) mesons is still one of the fascinating challenges of the strong interactions. The scope of the workshop was to identify and discuss key issues of the field in combination with relevant experimental and theoretical tools. The subject-matter may be summarized as follows.

- Properties of light (and not so light) mesons

The principal properties are masses and widths, where it is particularly important to extract the pole parameters from experiment in a model-independent way. Further structure information deals with (transition) form factors, decay rates and distributions, etc. Last but not least, the question of the nature of a resonance is of especial relevance.

- Dynamics of mesons

The dynamics of mesons reveals itself in terms of scattering, (production) cross sections, the generation of resonances, and the response to external probes. The interactions of pseudoscalars with pseudoscalars (PP), pseudoscalars with pseudovectors (PV), vectors with vectors (VV), plus additional electromagnetic interactions ( $PV\gamma$ , ...) are key processes to be understood, in particular, in view of the generation of resonances. Finally, also weak interactions yield valuable information on the dynamics of light mesons, mainly for kaons.

- Connection to QCD

A direct connection to QCD is provided by lattice field theory. In terms of effective theories, an important link is given by chiral symmetry in terms of Ward identities. The interplay of three distinct symmetry-breaking mechanisms (dynamical spontaneous symmetry breaking, explicit symmetry breaking due to the quark masses, and the  $U(1)$  axial anomaly) generates an extremely rich physics case. In this context, the  $\eta-\eta'$  system provides a unique stage for studying all three mechanisms simultaneously.

- Precision calculations

It is compulsory to perform precision calculations for at least a few key (strong-interaction) quantities such as, e.g., pion scattering lengths, the  $\pi^0 \rightarrow \gamma\gamma$  decay rate,

etc. The inclusion of isospin-symmetry breaking in terms of different  $u$ - and  $d$ -quark masses as well as electromagnetism plays an important role. Moreover, precision calculations are needed for observables relevant for essential Standard Model predictions.

- Rare or forbidden decays

In parallel to the hadronic decays discussed above, there are many  $C$  and  $CP$  violating decay modes of  $\eta$  and  $\eta'$  mesons. In the next years, the huge collected data samples will allow us to improve the upper limits on several of these branching fractions by at least one order of magnitude.

- Theoretical tools

The main theoretical tools discussed at the workshop include chiral perturbation theory, unitarized chiral dynamics, phenomenological approaches including quantum corrections and various applications of dispersion relations.

- Experimental tools

The experimental study of light meson dynamics is based on exclusive measurements of meson decays with large-acceptance detectors. At the workshop recent results and perspectives of the BESIII, Crystal Ball, KLOE, NA48/62 and WASA experiments were presented and discussed. One focus is the large number of charged and neutral  $\eta$ ,  $\eta'$ ,  $K$  and  $\omega$  decays which are intimately related to the low-energy dynamics of QCD. The experiments differ in the meson production mechanisms and background conditions as well as their capabilities in calorimetry and tracking, providing complementary approaches to the measurements.

Different experiments also have access to different regions of the electromagnetic transition form factors, allowing a quantitative connection between the time-like and the space-like regions.

We expect to improve the available statistics on  $K^\pm$ ,  $\eta$ ,  $\eta'$  and  $\omega$  mesons by several orders of magnitude within the next few years.

We acknowledge the support of the Deutsche Forschungsgemeinschaft DFG through the Collaborative Research Center “The Low-Energy Frontier of the Standard Model” (SFB 1044).

This work is a part of the activity of the SFB 1044:

[<http://sfb1044.kph.uni-mainz.de/sfb1044/>]

## 2 Summaries of the talks

### 2.1 The Odd Intrinsic Parity Sector of Chiral Perturbation Theory

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The chiral anomaly started with the decay  $\pi^0 \rightarrow \gamma\gamma$  [1] and its conflict with the naive Ward identities as solved by the discovery of the chiral anomaly [2]. At the same time current algebra and effective Lagrangians started but no naive Lagrangian with the correct chiral invariance was found. Ref. [3] solved the problem by directly integrating the anomalous divergence of [2] resulting in an effective action formulated in five dimensions. Witten[4] clarified the structure of this effective action, known as the Wess-Zumino-Witten (WZW) term. Another aspect is intrinsic parity, which is like parity but without its space-time part. A Lorentz-invariant Lagrangian that has parity, is also intrinsic parity invariant except when  $\epsilon_{\mu\nu\alpha\beta}$  is present. Processes with an odd number of pseudo-scalars thus require an  $\epsilon_{\mu\nu\alpha\beta}$ , hence the close connection of odd-intrinsic-parity and the anomaly, reviewed in e.g. [5].

Discussion of chiral logarithms started in the 1970s. For  $\pi^0, \eta \rightarrow \gamma\gamma$  they were found to vanish [6] in agreement with the naive expectation from the anomaly nonrenormalization theorem. Corrections were however found for the same process with one off-shell photon [7, 8]. The reason this is allowed is that the WZW term describes the anomaly but higher order terms that are chiral invariant can contribute to the same processes. But also loop diagrams including the WZW vertices must be fully invariant. This is true for the full divergence structure [9], see also [10]. The full version of the NLO Lagrangian was obtained in [11]. The two-flavour one including virtual photons is also known [12].

The decay  $\pi^0 \rightarrow \gamma\gamma$  is the main test of the anomaly. There are two precise experiments, PRIMEX [13] and CERN [14]. The theory has an enhancement over the anomaly predictions resulting mainly from  $\pi^0$ - $\eta$ - $\eta'$  mixing [12, 15]. Electromagnetic [12] and higher loop effects are quite small [16, 17]. A recent review is [18]. The agreement of the prediction of  $8.1 \pm 0.1$  eV is in good agreement with the measurement  $7.82 \pm 0.22$  eV, a test to about 3%.

The other main test,  $\pi\gamma \rightarrow \pi\pi$ , is not quite as precise. The main measurement [19] agrees satisfactorily with theory after including the one-loop corrections [20] and the surprisingly large electromagnetic corrections [21]. Higher order leading logarithms [17] are small. The evaluation from  $\pi e \rightarrow \pi\pi e$  [22] has a similar agreement with the predictions, to about 10%.

There are also anomalous form-factors in several weak decays. The precision varies but allows for clear tests of the *sign* of the anomaly. The ChPT calculations are in [23]. There are more processes that have the anomaly. Many are treated in other talks at this conference. e.g.  $\eta, \pi^0 \rightarrow \gamma^*\gamma^*$  or  $\eta \rightarrow \pi^+\pi^-\gamma$  including corrections from dispersion theory. Some oddities that allow in some domains of phase space for interesting effects are the processes  $\gamma\gamma \rightarrow 3\pi$  and  $\eta \rightarrow \pi\pi\gamma\gamma$ , known at tree level [24] and at one-loop [25].

The NLO Lagrangian is known but only partial fits of the parameters to experiment exist [26]. There exists many estimates, starting with the HLS model in [9] and the chiral quark model [27] and the full resonance saturation study [28].

Finally, some higher loops are known, two-loops for  $\pi^0 \rightarrow \gamma\gamma$  [16], partial results for  $\eta \rightarrow \gamma\gamma$  [29] and various leading logarithms up to six loops [17].

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## 2.2 $\eta$ - $\eta'$ mixing: overview

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The subject of  $\eta$ - $\eta'$  mixing is now becoming interesting in view of the present and forthcoming experiments at COSY (Jülich), DAPHNE (Frascati), ELSA (Bonn), MAMI (Mainz), VEPP-2000 (BINP, Novosibirsk), CEBAF (JLAB), BEPCII/BESIII (Beijing) and B-factories (BABAR, Belle and Belle II) where many different processes involving  $\eta$  and/or  $\eta'$  mesons are/will be measured abundantly and precisely as compared to earlier experiments.

Relevant topics concerning  $\eta$ - $\eta'$  mixing are the mixing parameters, that is, the pseudoscalar decay constants associated with  $\eta$  and  $\eta'$  and the related mixing angles in the octet-singlet and quark-flavour bases, the possibility of a gluonic content in the  $\eta'$  wave function, and the different sets of observables ( $V \rightarrow P\gamma$  decays, with  $V = \rho, \omega, \phi$  and  $P = \eta, \eta', J/\psi \rightarrow VP$  decays, and  $\eta$  and  $\eta'$  transition form factors, among the most precise sets) where these parameters can be extracted from.

Concerning the mixing parameters, a brief introductory summary is the following. There are two kinds of mixing, that of mass eigenstates and that of decay constants. The mixing of mass eigenstates consists of a rotation matrix described in terms of single mixing angle,  $\theta_P$  in the octet-singlet basis and  $\phi_P$  in the quark-flavour basis, that connects the mathematical states,  $\eta_8$  and  $\eta_0$  or  $\eta_q$  and  $\eta_s$ , depending on the basis, to the physical states  $\eta$  and  $\eta'$ . Both mixing angles are related through  $\theta_P = \phi_P - \arctan \sqrt{2}$ . In this mixing scheme three assumptions are implicit: i) there is no mixing with other pseudoscalars ( $\pi^0$ ,  $\eta_c$ , radial excitations, glueballs...); ii) the mixing angle is real (supported by the fact that  $\Gamma_{\eta, \eta'} \ll m_{\eta, \eta'}$ ); and iii) there is no energy dependence. The mixing of decay constants is characterized by  $\langle 0 | A_\mu^{a(i)} | \eta^{(i)}(p) \rangle = i\sqrt{2} F_{\eta^{(i)}}^{a(i)} p_\mu$ , with  $a = 8, 0$  ( $i = q, s$ ) and  $A_\mu^{a(i)}$  the corresponding axial-vector current. The four independent decay constants can be parameterised in terms of either  $F_{8,0}$ , the octet and singlet decay constants, and two mixing angles  $\theta_{8,0}$ , in the octet-singlet basis, or  $F_{q,s}$ , the light-quark and strange decay constants, and the mixing angles  $\phi_{q,s}$ , in the quark-flavour basis, respectively. Are all these mixing angles related? To answer this question, one must resort to Large- $N_c$  Chiral Perturbation Theory [1], where the effects of the pseudoscalar singlet  $\eta_0$  are treated perturbatively in a simultaneous expansion in  $p^2$ ,  $m_q$  and  $1/N_c$ . In this framework, one can see: i) that a one mixing angle scheme can only be used at leading order in this expansion, where  $\theta_8 = \theta_0 = \theta_P$  (or  $\phi_q = \phi_s = \phi_P$ ) and the decay constants are equal; ii) that at next-to-leading order the two mixing angles scheme must be used, thus making a difference between  $\theta_8$  and  $\theta_0$  and with respect to  $\theta_P$  (or similarly between  $\phi_q$  and  $\phi_s$  and with respect to  $\phi_P$ ) and where the decay constants are all different among themselves; and iii) that the mixing structure of the decays constants and the fields is exactly the same. For a compendium of formulae see Refs. [2, 3, 4, 5]. At the same time, one can also see that  $\sin(\theta_8 - \theta_0) \propto (F_K^2 - F_\pi^2)$ , a  $SU(3)$ -breaking effect expected to be of the order of 20% ( $F_K/F_\pi \simeq 1.2$ ), and  $\sin(\phi_q - \phi_s) \propto \Lambda_1$ , an OZI-rule

breaking parameter expected to be small. In the FKS scheme [6], this  $\Lambda_1$  parameter is assumed to be negligible, a hypothesis that is tested experimentally since the two mixing angles are seen to be compatible [5]. If one forces this equality,  $\phi_q = \phi_s = \phi_P$ , which is not based in theory, the result of the fit is  $F_q/F_\pi = 1.10 \pm 0.03$ ,  $F_s/F_\pi = 1.66 \pm 0.06$ , and  $\phi_P = (40.6 \pm 0.9)^\circ$  [5]. Therefore, a recommendation for experimental collaborations would be to use for the time being (until the achieved accuracy permits to distinguish between  $\phi_q$  and  $\phi_s$ ) the quark-flavour basis in their analyses. To finish, just to mention that the decay constants  $F_\eta$  and  $F_{\eta'}$  do not exist similarly to  $F_\pi$  or  $F_K$  but instead the four different decays constants mentioned before, in one basis or the other, must be used for the  $\eta$ - $\eta'$  system. The interested reader can use Ref. [6] as a reference text for a complete introduction to these topics and a detailed list of publications and analyses prior to year 2000.

Concerning the possible gluonic content in the  $\eta'$  wave function, two complete and precise sets of experimental data haven't taken into account to explore this possibility: the  $V \rightarrow P\gamma$  decays, with  $V = \rho, \omega, \phi$  and  $P = \eta, \eta'$ , and the  $J/\psi \rightarrow VP$  decays. In the first case, using a very general model for  $VP\gamma$  transitions [7], one gets  $\phi_P = (41.4 \pm 1.3)^\circ$  and  $Z_{\eta'}^2 = 0.04 \pm 0.09$ , or, equivalently,  $|\phi_{\eta'G}| = (12 \pm 13)^\circ$  (the parameter  $Z_{\eta'}$  weights the amount of gluonium in the wave function and  $\phi_{\eta'G} = -\arcsin Z_{\eta'}$ ), that is, absence of gluonium in the  $\eta'$  [8]. This result is in contradiction with the experimental analysis performed by the KLOE Collaboration, where, using several ratios of  $V \rightarrow P\gamma$  decays, described by the same model as before, in addition to the ratio  $\eta'/\pi^0 \rightarrow \gamma\gamma$ , they found  $\phi_P = (40.4 \pm 0.6)^\circ$  and  $Z_{\eta'}^2 = 0.12 \pm 0.04$  [9], thus confirming their first analysis with the results  $\phi_P = (39.7 \pm 0.7)^\circ$  and  $Z_{\eta'}^2 = 0.14 \pm 0.04$  [10]. The reason for the discrepancy between the first phenomenological analysis mentioned above and the former two experimental analyses is the inclusion in the latter of the ratio  $\eta'/\pi^0 \rightarrow \gamma\gamma$  in the fits. This sole observable makes the difference. However, we believe that the way KLOE characterises this ratio, as a function of  $F_q$ ,  $F_s$ ,  $\phi_P$ , and, simultaneously,  $Z_{\eta'}$  is a contradiction in terms, since Chiral Perturbation Theory assumes that  $\eta$  and  $\eta'$  are quark-antiquark bound states. In the case of  $J/\psi \rightarrow VP$  decays, the values obtained were  $\phi_P = (44.6 \pm 4.4)^\circ$  and  $Z_{\eta'}^2 = 0.29^{+0.18}_{-0.26}$  [11], thus drawing a conclusion less definitive but in accord with the  $V \rightarrow P\gamma$  phenomenological analysis. Anyway, more refined experimental data will contribute decisively to clarify this issue. For completion, when the gluonic content of the  $\eta'$  is not allowed,  $Z_{\eta'} = 0$ , the fitted value of the  $\eta$ - $\eta'$  mixing angle in the quark-flavour basis is found to be  $\phi_P = (41.5 \pm 1.2)^\circ$ , from  $V \rightarrow P\gamma$  decays [8], and  $\phi_P = (40.7 \pm 2.3)^\circ$ , from  $J/\psi \rightarrow VP$  decays [11], respectively. Other relevant analyses on this topic are Refs. [12, 13].

Finally, a more recent and novel approach for the extraction of the  $\eta$ - $\eta'$  mixing parameters is the analysis of the  $\eta$  and  $\eta'$  transition form factors in the space-like region at low and intermediate energies in a model-independent way through the use of rational approximants (see P. Masjuan's contribution to these proceedings for more details). Using the normalization of the form factors as obtained from the experimental  $\eta^{(\prime)} \rightarrow \gamma\gamma$  decay widths as well as the fitted result for the asymptotic value of the  $\eta$  form factor, one gets  $F_q/F_\pi = 1.06 \pm 0.01$ ,  $F_s/F_\pi = 1.56 \pm 0.24$ , and  $\phi_P = (40.3 \pm 1.8)^\circ$  [14], in nice agreement with previous results, a bit less precise but very promising for the near future if more space- and time-like experimental data for these form factors are released together with a more precise measurement of the decay widths.

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## 2.3 $\eta$ and $\eta'$ physics at BESIII

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Both  $\eta$  and  $\eta'$ , discovered about half of a century ago, are two important states in the lightest pseudoscalar nonet, which attracts considerable interest in the decays both theoretically and experimentally because of their special roles in low energy scale quantum chromodynamics theory. Their dominant radiative and hadronic decays were observed and well measured, but the study of their anomalous decays is still an open field. A sample of 225.3 million  $J/\psi$  events taken at the BESIII detector in 2009 offers a unique opportunity to study  $\eta$  and  $\eta'$  decays via  $J/\psi \rightarrow \gamma\eta(\eta')$  or  $J/\psi \rightarrow \phi\eta(\eta')$ .

With a new level of precision, the Dalitz plot parameters for  $\eta' \rightarrow \pi^+\pi^-\eta$  are determined in a generalized and a linear representation [1]. In general the results are in reasonable agreement with the previous measurements and the C-parity violation is not evident. The statistical error of the parameters are still quite large, much more data strongly needed to provide a more stringer test of the chiral theory. The decays of  $\eta' \rightarrow \pi^+\pi^-e^+e^-$  and  $\eta' \rightarrow \pi^+\pi^-\mu^+\mu^-$  were also studied via  $J/\psi \rightarrow \gamma\eta'$  [2]. A clear  $\eta'$  peak is observed in the  $M_{\pi^+\pi^-e^+e^-}$ -mass spectrum, and the branching fraction is measured to be  $B(\eta' \rightarrow \pi^+\pi^-e^+e^-) = (2.11 \pm 0.12 \pm 0.14) \times 10^{-3}$ , which is in good agreement with theoretical predictions [3] and the previous measurement [4], but is determined with much higher precision. The mass spectra of  $M_{\pi^+\pi^-}$  and  $M_{e^+e^-}$  are also consistent with the theoretical predictions [3] that  $M_{\pi^+\pi^-}$  is dominated by  $\rho^0$ , and  $M_{e^+e^-}$  has a peak just above  $2m_e$ . No  $\eta'$  signal is found in the  $M_{\pi^+\pi^-\mu^+\mu^-}$  mass spectrum, and the upper limit is determined to be  $B(\eta' \rightarrow \pi^+\pi^-\mu^+\mu^-) < 2.9 \times 10^{-5}$  at the 90% confidence level. To test the fundamental symmetries, a search for P and CP violation decays of  $\eta/\eta' \rightarrow \pi^+\pi^-, \pi^0\pi^0$  was performed [5]. No evident signals were observed, and then the branching fraction upper limits,  $B(\eta \rightarrow \pi^+\pi^-) < 3.9 \times 10^{-4}$ ,  $B(\eta \rightarrow \pi^0\pi^0) < 6.9 \times 10^{-4}$ ,  $B(\eta' \rightarrow \pi^+\pi^-) < 5.5 \times 10^{-5}$  and  $B(\eta' \rightarrow \pi^0\pi^0) < 4.5 \times 10^{-4}$ , are presented at the 90% confidence level.

In addition we made an attempt to search for their invisible and weak decays via  $J/\psi \rightarrow \phi\eta$  and  $J/\psi \rightarrow \phi\eta'$  [6, 7]. These two-body decays provide a very simple event topology, in which the  $\phi$  meson can be reconstructed easily and cleanly with its dominant decays of  $\phi \rightarrow K^+K^-$ . Since the  $\phi$  and  $\eta(\eta')$  are given strong boosts in the  $J/\psi$  decay, the invisible decays of the  $\eta$  and  $\eta'$  were investigated with the mass spectra recoiling against  $\phi$ . We find no signal above background for the invisible decays of  $\eta$  and  $\eta'$ . To reduce the systematic uncertainty, the upper limits of the ratios,  $\frac{B(\eta \rightarrow \text{invisible})}{B(\eta \rightarrow \gamma\gamma)} < 2.6 \times 10^{-4}$  and  $\frac{B(\eta' \rightarrow \text{invisible})}{B(\eta' \rightarrow \gamma\gamma)} < 2.4 \times 10^{-2}$ , were obtained first at the 90% confidence level. Then, using the branching fractions of  $\eta(\eta') \rightarrow \gamma\gamma$ , the branching fraction upper limits at the 90% confidence level were determined to be  $B(\eta \rightarrow \text{invisible}) < 1.0 \times 10^{-4}$  and  $B(\eta' \rightarrow \text{invisible}) < 5.3 \times 10^{-4}$ . For the first time a search for the semileptonic weak decay modes  $\eta(\eta') \rightarrow \pi^+e^-\bar{\nu}_e$  was performed and no signal was observed. At the 90% confidence level, the semileptonic weak rates were given to be  $B(\eta \rightarrow \pi^+e^-\bar{\nu}_e + c.c.) < 1.7 \times 10^{-4}$  and  $B(\eta' \rightarrow \pi^+e^-\bar{\nu}_e + c.c.) < 2.2 \times 10^{-4}$ .

Based on the 225.3 million  $J/\psi$  events, we present the recent results on  $\eta$  and  $\eta'$  decays in this talk. To precisely test the fundamental symmetries and theoretical predictions, the larger statistics of  $\eta(\eta')$  decays are strongly needed. In 2012 the BESIII detector collected about 1 billion  $J/\psi$  events, four times larger than the sample taken in 2009, which allows us to update the study of  $\eta'$ , including the Dalitz plot analysis, the search for new decays, as well as the test to the fundamental symmetries. We believe that more interesting results will be coming soon in the near future.

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## 2.4 Hadron Physics Studies at KLOE/KLOE-2

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The KLOE experiment at the Frascati  $\phi$ -factory DAΦNE collected  $2.5 \text{ fb}^{-1}$  at the  $\phi$  meson peak and about  $240 \text{ pb}^{-1}$  below the  $\phi$  resonance ( $\sqrt{s} = 1 \text{ GeV}$ ), providing large samples of light mesons. The KLOE-2 detector has been upgraded with small angle tagging devices to detect electrons or positrons in  $e^+e^- \rightarrow e^+e^-X$  events and with an inner tracker and small angle calorimeters in the interaction region to increase the acceptance both for charged particles and photons. A new data taking is planned in years 2014-2015, aiming to collect  $5 \text{ fb}^{-1}$ . A detailed description of the experimental physics program can be found in Ref. [1].

The  $\eta \rightarrow \pi^+\pi^-\gamma$  decay dynamics has been studied to search for a possible contribution from chiral anomaly, a higher term of the ChPT Lagrangian describing the direct coupling of three pseudoscalar mesons with the photon [2]. The analysis has been performed using  $558 \text{ pb}^{-1}$ , where about  $25 \times 10^6$   $\eta$ 's are produced together with a monochromatic recoil photon ( $E_{\gamma\phi} = 363 \text{ MeV}$ ) through the radiative decay  $\phi \rightarrow \eta\gamma$ . The process  $\eta \rightarrow \pi^+\pi^-\pi^0$ , with similar event topology and negligible background contamination, has been used as normalization sample. The ratio of the partial decay widths [3],  $\frac{\Gamma(\eta \rightarrow \pi^+\pi^-\gamma)}{\Gamma(\eta \rightarrow \pi^+\pi^-\pi^0)} = 0.1856 \pm 0.0005_{\text{stat}} \pm 0.0028_{\text{syst}}$ , points for a sizable contribution of the direct term to the total width. The  $M_{\pi^+\pi^-}$  dependence has been parametrized with the model independent approach of Ref. [4].

The  $\eta \rightarrow \pi^+\pi^-\pi^0$  process is an isospin violating decay, sensitive to light quark mass difference [5]. Dalitz plot analysis, based on  $450 \text{ pb}^{-1}$ , have been performed at KLOE in 2008 [6] and have been used in dispersive analysis to extract the quark mass ratio [7, 8]. A new high statistics Dalitz plot analysis is in progress with an independent and larger ( $1.7 \text{ fb}^{-1}$ ) data set, using a new analysis scheme and improved Monte Carlo (MC) simulation. Preliminary fit results, reported in Tab. 1 are in agreement with previous KLOE measurement. Evaluation of systematics is in progress.

Table 1: Fit results for  $\eta \rightarrow \pi^+\pi^-\pi^0$  Dalitz plot analysis.

	$a$	$b$	$d$	$f$
KLOE08	$-1.090 \pm 0.005^{+0.008}_{-0.019}$	$0.124 \pm 0.006 \pm 0.010$	$0.057 \pm 0.006^{+0.007}_{-0.016}$	$0.14 \pm 0.01 \pm 0.02$
KLOE prel.	$-1.104 \pm 0.003$	$0.144 \pm 0.003$	$0.073 \pm 0.003$	$0.155 \pm 0.006$

Pseudoscalar production associated to internal conversion of the photon into a lepton pair allows the measurement of the form factor  $F_P(q_1^2 = M_\phi^2, q_2^2 > 0)$  in the kinematical region of interest for the VMD model. Detailed study of such decays has been performed using  $1.7 \text{ fb}^{-1}$  of data, both for  $\phi \rightarrow \eta e^+e^-$  and  $\phi \rightarrow \pi^0 e^+e^-$  processes. About 30,000  $\phi \rightarrow \eta e^+e^-$ ,  $\eta \rightarrow \pi^0\pi^0\pi^0$  candidates are present in the analyzed data set, with a residual background

contamination below 3%, providing a preliminary measurement of the branching fraction:  $\text{BR}(\phi \rightarrow \eta e^+ e^-) = (1.131 \pm 0.032_{\text{stat+norm}}^{+0.011}_{-0.006 \text{ syst}}) \times 10^{-4}$ . The resulting electron-positron invariant mass shape,  $M_{ee}$ , has been fitted using the decay parametrization from Ref. [9]. The preliminary value obtained for the slope of the transition form factor in the whole KLOE data set is:  $b_{\phi\eta} = (1.17 \pm 0.11_{\text{stat}}^{+0.09}_{-0.08 \text{ syst}}) \text{ GeV}^{-2}$ , in agreement with VMD predictions. For the decay  $\phi \rightarrow \pi^0 e^+ e^-$  no data are available on transition form factor. Dedicated analysis cuts strongly reduce the main background component of Bhabha scattering events to  $\sim 20\%$ , which still dominates for  $M_{ee} > 300 \text{ MeV}$ , while a sample of  $\sim 9000$  signal candidates is obtained. Studies are in progress to refine the evaluation of background contamination and of analysis efficiencies.

Data collected at  $\sqrt{s} = 1 \text{ GeV}$  have been used to study hadron production in  $\gamma\gamma$  interactions, providing the most precise measurement of the  $\Gamma(\eta \rightarrow \gamma\gamma)$  partial width from the measurement of the  $e^+ e^- \rightarrow e^+ e^- \eta$  cross section, using both neutral and charged  $\eta \rightarrow \pi\pi\pi$  decay channels [10]. The main background is due to resonant  $\phi \rightarrow \eta\gamma$  events, with an undetected recoil photon. After reducing background components with specific kinematical cuts, signal events are extracted by fitting with the expected Monte Carlo components the two-dimensional plot  $M_{\text{miss}}^2 - p_{L/T}$ , where  $M_{\text{miss}}^2$  is the squared missing mass and  $p_{L/T}$  is the  $\eta$  longitudinal/transverse momentum in the  $\pi^0\pi^0\pi^0/\pi^+\pi^-\pi^0$  decay. Combining the two measurements, the extracted value for the production cross section is:  $\sigma(e^+ e^- \rightarrow e^+ e^- \eta) = (32.7 \pm 1.3_{\text{stat}} \pm 0.7_{\text{syst}}) \text{ pb}$ . This value is used to extract the most precise measurement of the  $\eta \rightarrow \gamma\gamma$  partial width:  $\Gamma(\eta \rightarrow \gamma\gamma) = (520 \pm 20_{\text{stat}} \pm 13_{\text{syst}}) \text{ eV}$ .

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## 2.5 Dispersion theory to connect $\eta \rightarrow \pi\pi\gamma$ to $\eta \rightarrow \gamma^*\gamma$

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A dispersion integral is derived that connects data on  $\eta \rightarrow \pi^+\pi^-\gamma$  to the  $\eta \rightarrow \gamma\gamma^*$  transition form factor [1]. It is demonstrated that both reactions are controlled by two scales: a universal one driven by the  $\pi\pi$ -final state interactions (and of the order of the lightest vector meson mass) and one that is reaction specific [2]. A detailed analysis of the uncertainties is provided. We find for the slope of the  $\eta$  transition form factor at the origin  $b_\eta = (2.05^{+0.22}_{-0.10}) \text{ GeV}^{-2}$ . Using an additional, plausible assumption, one finds for the corresponding slope of the  $\eta'$  transition form factor,  $b_{\eta'} = (1.58^{+0.18}_{-0.13}) \text{ GeV}^{-2}$ . Both values are consistent with all recent data, but differ from some previous theoretical analyses. We regard this study, that provides a systematic improvement compared to the vector meson dominance approach backed by a sound theoretical method, as an important step towards a better quantitative control of the hadronic light-by-light scattering contribution to the muon anomalous magnetic moments [3].

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## 2.6 Dispersion theory and chiral dynamics: from light- to heavy-meson decays

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Dalitz plot studies of weak three-body decays of mesons with open heavy flavor (both  $D$  and  $B$ ) may play a key role in future precision investigations of CP violation, within and beyond the Standard Model. This is due to their much richer kinematic freedom compared to the (effective) two-body final states predominantly used to study CP violation at the  $B$  factories: the resonance-rich environment of multi-meson final states may help to enlarge small CP phases in parts of the Dalitz plot [1]. Traditionally, Dalitz plots have been analyzed experimentally in terms of isobar models: pairwise interaction between final-state particles, approximated in terms of Breit–Wigner resonances plus background terms. However, there is no way to separate resonant from non-resonant contributions in a model-independent way; some partial waves, most notably the pion–pion and pion–kaon S-waves (of isospin  $I = 0$  and  $I = 1/2$ , respectively), cannot be modeled in terms of Breit–Wigner functions at all; and finally, three-body interactions can modify the isobar picture significantly.

Dispersion relations represent a model-independent method to describe final-state interactions, based on input for (re)scattering phase shifts. If two strongly interacting particles are produced from a point source, the corresponding form factors can be described in terms of Omnès representations; see e.g. Ref. [2] for recent work on the pion vector, and Ref. [3] (as well as references therein) for the pion scalar form factor. For three hadrons in the final state, the Khuri–Treiman formalism [4] (applied in the formulation of Ref. [5]) allows to write down Omnès-like solutions including inhomogeneities, which are given by partial-wave-projected crossed-channel amplitudes. Such a system has been studied for the three-pion decays of the lightest isoscalar vector mesons  $\omega$  and  $\phi$  [6], which has been shown to describe the  $\phi \rightarrow 3\pi$  Dalitz plot perfectly. The phenomenological contact interactions required in the experimental analysis [7], which necessarily violate unitarity, thereby seem to emulate the non-trivial three-body rescattering effects not otherwise included. Very similar sets of equations can also be used to analyze the anomalous process  $\gamma\pi \rightarrow \pi\pi$  [8].

A further application of dispersion theory concerns the vector-meson transition form factors as measured in  $\omega/\phi \rightarrow \pi^0 \ell^+ \ell^-$  [9]: they only require the corresponding three-pion decay amplitudes and the pion vector form factor as input. The comparison to experimental data for  $\omega \rightarrow \pi^0 \mu^+ \mu^-$  obtained from heavy-ion reactions [10] however remains problematic.

An ongoing extension of dispersive Dalitz plot analyses concerns the decay  $D^+ \rightarrow \pi^+ \pi^+ K^-$ , with a richer structure of pion–pion and pion–kaon partial waves, dynamical coupling to the  $\pi^+ \pi^0 \bar{K}^0$  final state [11], and a larger number of subtraction constants to be fixed. Preliminary fits to data [12] in the kinematic region where elastic unitarity in  $\pi K$  scattering should still hold to good accuracy suggest a similar improvement through three-body rescattering as for the  $\phi \rightarrow 3\pi$  Dalitz plot [13]. Whether or not such three-body final states can be used to actually *learn* something about  $\pi K$  scattering phases in a

model-independent way remains to be investigated [14, 15].

The latter may be more straightforward for semileptonic decays, such as  $D \rightarrow \pi K \ell \nu$ , without a third strongly-interacting particle in the final state. However, even in such a case, left-hand singularities may be important, as has been demonstrated for the similar process  $B \rightarrow \pi \pi \ell \nu$  [16], an exclusive decay channel that potentially allows for an extraction of the CKM matrix element  $|V_{ub}|$ .  $B^*$ -pole terms dominate the amplitude at leading order in heavy-meson chiral perturbation theory [17] in the kinematic region of two very soft pions; dispersion theory allows to vastly extend the kinematic range of applicability, and to control the shape of the partial waves, including S-wave background to the presumed  $\rho$  dominance.

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## 2.7 Interactions of light with light mesons

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Electromagnetic probes are a good way to explore the intrinsic structure of hadrons. A second reason why the interactions between light mesons and photons are interesting comes from the present disagreement between the experimental value of the gyromagnetic ratio of the muon and its standard-model prediction (see, e.g., [1, 2] and references therein). The hadronic contributions to this gyromagnetic ratio constitute the largest uncertainty in the standard-model prediction. These contributions can be split into the hadronic vacuum polarization and the light-by-light scattering contribution. The former is directly related to a measurable quantity via dispersion theory. At present the latter requires hadronic-theory input. This calls for high-precision experiments and for a hadronic theory where the uncertainties can be reliably estimated. Concerning hadronic calculations in the resonance region we have not reached this aim yet. But steps are undertaken in this direction exploring different techniques and concepts.

One approach is based on a chiral Lagrangian for pseudoscalar and vector mesons complemented by rules how to assign specific levels of importance to various Feynman diagrams. (On purpose the phrase “power counting” is avoided until the impact of higher-order contributions has been studied systematically. This is presently under investigation.) The approach is well documented in the literature [6, 4, 5, 6, 7, 8, 9]. Relations to light-by-light scattering are manifold: Reactions of two photons to two pseudoscalar mesons are studied in [8]. Due to the intimate relation between photons and (neutral) vector mesons (same quantum numbers) electromagnetic transition form factors between vector and pseudoscalar mesons [5, 7] constitute particular kinematical situations of the coupling of a single pseudoscalar meson to two virtual photons.

To highlight one result of the Lagrangian approach the electromagnetic transition form factor for  $\omega$  to  $\pi^0$  is depicted on the left-hand side of figure 1. Obviously the overall description is good and much better than the traditional standard vector-meson dominance model. However, there is a clear mismatch between the NA60 dimuon data and calculations for the high-mass region close to the phase-space limit of the reaction  $\omega \rightarrow \pi^0 \mu^+ \mu^-$ . An independent confirmation of the NA60 results from a more exclusive experiment, e.g. in the decay reaction  $\omega \rightarrow \pi^0 e^+ e^-$ , would be extremely welcome.

A second approach to meson transition form factors is based on dispersion theory and excellent data for pion phase shifts and the (direct) pion vector form factor [13, 14, 15, 16, 17]. For the calculation of the pion-to-photon transition form factor one analyzes the possible hadronic inelasticities. For the reaction  $e^+ e^- \rightarrow \gamma \pi^0$  up to about 1 GeV the relevant intermediate hadronic states are two pions (isospin 1) or three pions (isospin 0). Thus for the isospin-1 case the imaginary part of the scattering amplitude is given by the consecutive reactions  $e^+ e^- \rightarrow \pi^+ \pi^-$  and  $\pi^+ \pi^- \rightarrow \gamma \pi^0$ . The former is just the well-known pion vector form factor, the latter has been calculated in the dispersive approach in [15]. Note that the previously discussed omega transition form factor has also been calculated in the dispersive

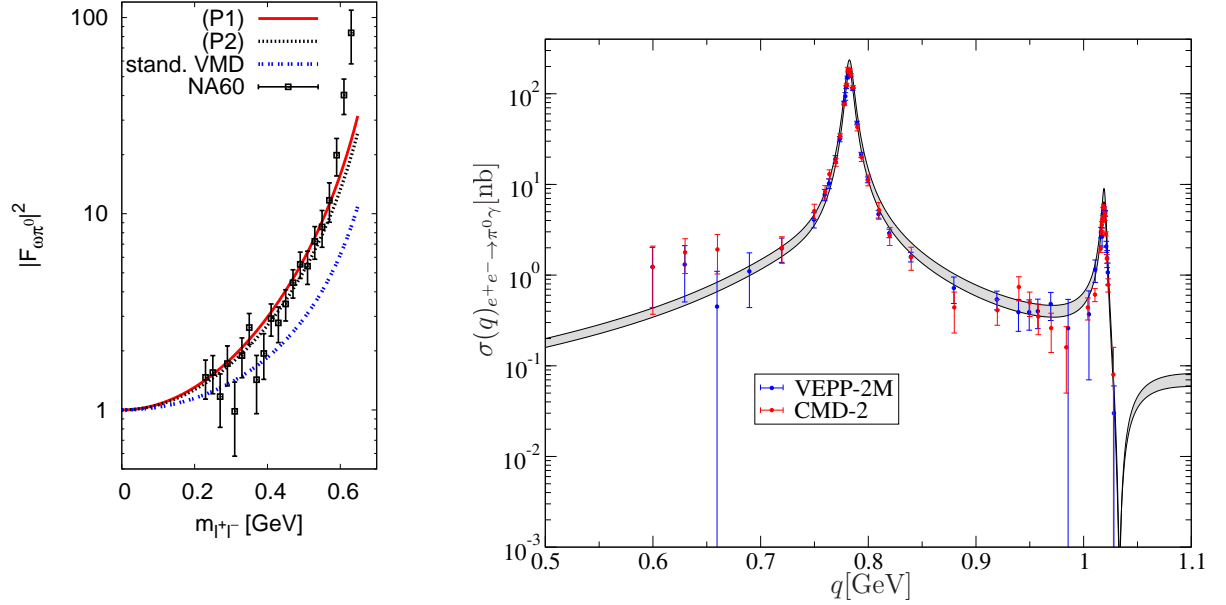


Figure 1: *Left-hand side:* The  $\omega$  transition form factor from the Lagrangian approach (full red line) as compared to data from the NA60 experiment [10] and to the result from standard vector-meson dominance (blue dashed line). See [5] for details. *Right-hand side:* The cross section for  $e^+e^- \rightarrow \gamma\pi^0$  (pion transition form factor) from the dispersive approach [18] as compared to data from Novosibirsk [11, 12].

approach [14]. A fully dispersive treatment of the case where the dielectron has isospin 0 in the reaction  $e^+e^- \rightarrow \gamma\pi^0$  would require a proper handling of the amplitudes  $e^+e^- \rightarrow \pi^+\pi^-\pi^0$  and  $\pi^+\pi^-\pi^0 \rightarrow \gamma\pi^0$ . This is technically beyond the scope of present works and also lacks the necessary differential data as input. However, the isospin-0 case is dominated at low energies by the narrow resonances  $\omega$  and  $\phi$ . Therefore a dispersively improved Breit-Wigner approach is pursued here. Parameters (peak positions, peak heights and polynomial background terms) are chosen such that the reaction  $e^+e^- \rightarrow \pi^+\pi^-\pi^0$  is properly described. Using an unsubtracted dispersion relation, one obtains the pion transition form factor displayed in figure 1, right-hand side. In [14] it has been shown that the decay widths  $\omega, \phi \rightarrow \gamma\pi^0$  as obtained by the same technique are precise on a ten percent level. The corresponding uncertainty has been added to the isospin-0 part of the pion transition form factor resulting in the gray band shown in figure 1, right-hand side. Obviously a very decent description of the pion transition form factor can be obtained in this way [18]. It opens the way for the calculation of the spacelike part of the pion transition form factor and eventually for the corresponding double-virtual form factor, which in turn enters as one important contribution into the light-by-light scattering amplitude.

Several present high-statistics experiments allow for detailed studies of rare meson decays in the meson-mass range of 1 GeV. In particular the  $\eta'$  meson obtains and deserves a lot of attention since its properties are intimately related to the chiral anomaly. The vector mesons in this mass range seem to be much less appealing since they are ordinary quark-

antiquark states and their main properties are not dominated in a fancy way by any broken or unbroken symmetry. However, electromagnetic probes of hadrons cannot be understood (in particular at a high-precision level) without understanding the vector mesons. This remark even applies to the  $\eta'$  decays involving photons from which one would like to learn something about the chiral anomaly. This strongly suggests to study not only  $\eta'$  decays but with the same dedication also rare decays of vector mesons, in particular also of omega mesons. For instance improved experimental differential data for the poorly known reactions  $\omega/\phi \rightarrow \pi^0 e^+ e^-$  and  $\omega \rightarrow \gamma + 2\pi$  would be highly desirable. Among other aspects they would help to sharpen the theory tools outlined above. Both mentioned reactions have a clear connection to light-by-light scattering: The decay  $\omega/\phi \rightarrow \pi^0 e^+ e^-$  is intimately related to one particular kinematical region of the pion transition form factor where one invariant mass is fixed to the vector-meson mass. The decay  $\omega \rightarrow \gamma + 2\pi$  provides the lowest-energetic inelasticity for  $\omega \rightarrow 3\gamma$  which in turn is directly related to light-by-light scattering with three photons onshell and one with the invariant mass of the  $\omega$  meson.

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## 2.8 Chiral dynamics with vector mesons

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The light vector mesons play a crucial role in the hadrogenesis conjecture [1, 2, 3, 4, 5, 6, 7]. Together with the Goldstone bosons they are identified to be the “quasi-fundamental” hadronic degrees of freedom that are expected to generate the meson spectrum. For instance it was shown that the leading chiral interaction of Goldstone bosons with the light vector mesons generates an axial-vector meson spectrum that is quite close to the empirical spectrum [2].

Though it is well known how to incorporate more massive degrees of freedom into the chiral Lagrangian, it is a challenge how to organize systematic applications. The key issue is the identification of an optimal set of degrees of freedom in combination with the construction of power counting rules. A novel counting scheme for the chiral Lagrangian which includes the nonet of light vector mesons in the tensor field representation was explored in [6, 7]. It is based on the hadrogenesis conjecture and large- $N_c$  considerations [1, 2, 3, 4, 5]. The counting scheme would be a consequence of an additional mass gap of QCD in the chiral limit, that may arise if the number of colors increases. Whether it leads to a fully systematic effective field theory is an open issue.

The leading-order hadrogenesis Lagrangian as constructed in [6, 7] was tested in various applications so far. Most of the low-energy parameters can be estimated by hadronic and electromagnetic properties of the vector mesons evaluated at tree-level [6, 7, 8, 9]. Applications to coupled-channel systems [10, 11] are based on a novel unitarization scheme that is justified in the presence of long and short-range forces [12, 13, 14, 10, 11, 15]. A first systematic analysis of pion-pion and pion-kaon scattering can be found in [10]. Given the fact that at leading order there is no free parameter a remarkable reproduction of the empirical phases shifts was obtained. Like in previous coupled-channel studies of such systems various scalar resonances are generated dynamically. As a further application photon fusion reactions were considered in [11]. In this case a few low-energy parameters were adjusted to the data set. In our scheme already at leading order the vector-meson exchange processes play an important role. This is contrasted by the standard  $\chi$ PT approach where the leading order interactions are not affected by vector-meson exchange processes [16]. In this case the subleading counter terms may be estimated by a saturation ansatz in terms of vector-meson exchange processes [16].

At higher energies further resonances come into play. In principle, also for instance the tensor resonances  $f_2(1270)$  and  $a_2(1320)$  are expected to be naturally generated within our approach from vector-vector interactions [5]. However, a significant application of the hadrogenesis Lagrangian to the scattering of two vector mesons is quite a challenge. So far no realistic computations based on the chiral Lagrangian have been performed. The basis for the systematic inclusion of pairs of vector mesons as coupled-channel states has been laid

out recently in [18]. In a first step it is necessary to identify partial-wave amplitudes that have convenient analytic properties [12, 17, 18] as to be used in the unitarization scheme [12, 13, 14, 10, 11, 15]. Once intermediate states with two vector mesons are considered there are almost always long-range forces implied by t- or u-channel exchange processes that lead to non-trivial left-hand branch points in the partial-wave amplitudes. The positions of left- and right-hand branch cuts almost always overlap.

There is a subtle limitation of algebraic or separable approaches, if applied to such a coupled-channel situation. The partial-wave scattering amplitudes have necessarily unphysical left-hand branch points [2, 10]. This holds at any finite truncation unless the K-matrix ansatz, which is at odds with micro causality, is imposed. Though such unphysical left-hand branch violate the micro-causality condition they do not necessarily always lead to numerically significant effects in the physical region. If all considered left-hand branch points are below the smallest considered threshold, i.e. the left- and right hand branch cuts do not overlap, the presence of unphysical branch points are not really problematic. However, once a left-hand branch point of a heavy channel like the two-vector meson channel is located right to the threshold of a lighter channel an algebraic approach can no longer be justified.

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## 2.9 $\eta$ Transition Form Factors from Rational Approximants

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The pseudoscalar transition form factor (TFF) describes the effect of the strong interaction on the  $\gamma^*\gamma^* - P$  transition, where  $P = \pi^0, \eta, \eta' \dots$ , and is represented by a function  $F_{P\gamma^*\gamma^*}(q_1^2, q_2^2)$  of the photon virtualities  $q_1^2$ , and  $q_2^2$ .

From the experimental point of view, one can study such TFF from both space-like and time-like energy regimes. The time-like TFF can be accessed from a single Dalitz decay  $P \rightarrow l^+l^-\gamma$  process which contains an off-shell photon with the momentum transfer  $q_1^2$  and defines a  $F_{P\gamma^*\gamma}(q_1^2, 0)$  covering the  $4m_l^2 < q^2 < m_P^2$  region. The space-like TFF can be accessed in  $e^+e^-$  colliders by the two-photon-fusion reaction  $e^+e^- \rightarrow e^+e^-P$ . The common practice is to extract the TFF when one of the outgoing leptons is tagged and the other is not, that is, the single-tag method. The tagged lepton emits a highly off-shell photon with the momentum transfer  $q_1^2 \equiv -Q^2$  and is detected, while the other, untagged, is scattered at a small angle and its momentum transfer  $q_2^2$  is near zero, i.e.,  $F_{P\gamma^*\gamma}(Q^2) \equiv F_{P\gamma^*\gamma}(-Q^2, 0)$ .

Theoretically, the limits  $Q^2 = 0$  and  $Q^2 \rightarrow \infty$  are well known in terms of the axial anomaly in the chiral limit of QCD [1] and pQCD [2], respectively. The TFF is then calculated as a convolution of a perturbative hard-scattering amplitude and a gauge-invariant meson distribution amplitude (DA) [3] which incorporates the nonperturbative dynamics of the QCD bound-state [2]. Some model needs to be used either for the DA or the TFF itself. The discrepancy among different approaches reflects the model-dependency of that procedure. A different procedure might be, then, desirable.

We propose [4] to use a sequence of rational approximants called Padé approximants (PA) [5] constructed from the Taylor expansion of the  $F_{\eta\gamma^*\gamma}(Q^2)$  to fit the space- and time-like experimental data, Refs. [6] and [7] resp., and obtain, in such a way, the derivatives of the  $F_{\eta\gamma^*\gamma}(Q^2)$  at the origin of energies in a simple, systematic and model-independent way [8]. Including the decays of the  $\eta^{(\prime)} \rightarrow \gamma\gamma$  in our set of data, we can systematically predict the slope and the curvature of both  $\eta^{(\prime)}$ -TFFs. The low-energy parameters obtain with this method can be used to constrain the hadronic models used to account for the light-by-light scattering contribution part of the anomalous magnetic moment of the muon [4, 9], rare  $\eta$  decays and continuum cross section determinations in the charmonium region [4]. Reference [4] also provides with parameterizations for such form factors valid for the whole space-like energy range. Notice, however, that even though the procedure followed here is based on model-independent methods, the PA fit does not provide with an extraction of the resonance pole exchanged in the process since PA cannot be analytically continued into the complex plain where poles are supposed to lie [10]. The same comment applies for interpreting the outcome of a fit with a Vector Meson Dominance model (its pole parameter) as the vector meson mass participating in the process [11].

The physical  $\eta$  and  $\eta'$  mesons are an admixture of the  $SU(3)$  Lagrangian eigenstates [12].



Deriving the parameters governing the mixing is a challenging task. Usually, these are determined through the use of  $\eta(') \rightarrow \gamma\gamma$  decays as well as vector radiative decays into  $\eta(')$  together with  $\Gamma(J/\Psi \rightarrow \eta'\gamma)/\Gamma(J/\Psi \rightarrow \eta\gamma)$  [12]. However, since pQCD predicts that the asymptotic limit of the TFF for the  $\eta(')$  is essentially given in terms of these mixing parameters [13], we use our TFF parametrization to estimate the asymptotic limit and further constrain the mixing parameters with compatible results compared to standard (but more sophisticated) determinations.

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## 2.10 $\eta - \pi$ isospin violating form factors

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The fact that isospin symmetry appears to be nearly exact in nature is linked to the peculiar mass pattern of the three lightest quarks in QCD:  $m_d - m_u \ll m_s$  and  $m_s \ll 1$  GeV. One of the goals of the chiral effective low-energy theory of QCD is to arrive at a consistent and precise determination of ratios of the light quark masses based on experimental measurements involving light mesons. At present, the determination of isospin breaking quark mass ratios like  $1/Q^2 = (m_u^2 - m_d^2)/(m_s^2 - m_{ud}^2)$  from different observables lead to differences as large as 20%. This has triggered efforts, on the experimental side, for performing improved measurements of the  $\eta \rightarrow 3\pi$  amplitude [1, 2, 3, 4, 5], which is proportional to  $1/Q^2$  to a high accuracy. On the theory side, it was proposed to supplement the chiral expansion with dispersive methods in order to improve the treatment of the final-state interactions [6, 7], based on the framework originally proposed by Khuri and Treiman [8].

There has also been progress in measurements of isospin breaking in  $K_{l3}$  form factors (see [9]). We reconsider here the analogous  $\eta_{l3}$  form factors, which are vanishing in the isospin limit, and discuss their relation with the  $\eta \rightarrow 3\pi$  amplitude and with the  $K_{l3}$  form factors. While the branching fraction for  $\eta_{l3}$  decays are too small for observation, this is not the case for the  $\tau$  decay mode:  $\tau \rightarrow \eta\pi\nu$ . The related isospin suppressed  $\eta - \pi$  form factors could in principle be measured with some precision at future  $\tau$ -charm factories and at Belle-II which was not possible at past  $B$  factories because large backgrounds. This has motivated us to reconsider the evaluation of these isospin violating form factors. References to previous work on this subject can be found in ref. [10].

The basic method for the evaluation of the  $\eta - \pi$  form factors in the energy region of the light resonances is to combine ChPT results with general properties of analyticity and unitarity. From analyticity, one can write a dispersive representation for the vector form factor,

$$f_+^{\eta\pi}(s) = f_+^{\eta\pi}(0) + s\dot{f}_+^{\eta\pi}(0) + \frac{s^2}{\pi} \int_{4m_\pi^2}^{\infty} ds' \frac{\text{disc}[f_+^{\eta\pi}(s')]}{(s')^2(s' - s)}. \quad (1)$$

One can show (using the method of ref. [11]) that the usual analyticity properties (in particular, the absence of anomalous thresholds) holds in the present case in spite of the fact that the  $\eta$  meson is unstable. The values of the form factor and its derivative at  $s = 0$ , needed in eq. 1 may be taken from the NLO chiral calculations [12, 13]. In particular, a chiral low-energy theorem was derived in ref. [12] which enables one to relate  $f_+^{\eta\pi}(0)$  with the  $K_{l3}$  form factor ratio  $f_+^{K^+\pi^0}(0)/f_+^{K^0\pi^+}(0)$ . Next, one can express  $\text{disc}[f_+^{\eta\pi}(s')]$  in eq. 1 using unitarity: the dominating contribution below 1 GeV reads,

$$\text{disc}[f_+^{\eta\pi}(s)]_{\pi\pi} = -\theta(s - 4m_\pi^2) \frac{s - 4m_\pi^2}{16\pi \sqrt{\lambda_{\eta\pi}(s)}} F_V^\pi(s) \times \frac{1}{2} \int_{-1}^1 dz z T_{\pi^0\pi^+ \rightarrow \eta\pi^+}^*(s, t(z)). \quad (2)$$

It is proportional to the well known pion form factor  $F_V^\pi$  and to the  $\eta \rightarrow \pi^0\pi^+\pi^-$  amplitude,

projected on the  $P$ -wave. This amplitude is needed partly in an unphysical region: we have determined it based on a four-parameter family of numerical solutions of the Khuri-Treiman equations. These four parameters can be determined completely from the NLO chiral amplitude by solving a set of four matching equations. Doing so, one predicts the Dalitz plot parameters for the charged  $\eta$  decay mode to be slightly different from those measured [9], in particular the Dalitz parameter  $d$  which probes the  $(t - u)^2$  dependence, is found to be larger by  $\simeq 30\%$ . The sensitivity of the form factor shape to the  $\eta$  decay amplitude is illustrated by fig. 2 which compares the results from an amplitude as predicted by matching and from an amplitude fitted to experiment.

A full estimate of the  $\eta\pi$  spectral function also requires input for the scalar form factor  $f_0^{\eta\pi}$ . This form factor contains information on the nature of the scalar resonance  $a_0(980)$  via its coupling to the  $\bar{u}d$  scalar operator. We have performed an estimate based on ChPT and dispersion relations: in this framework an exotic nature manifest itself by the presence of a zero.

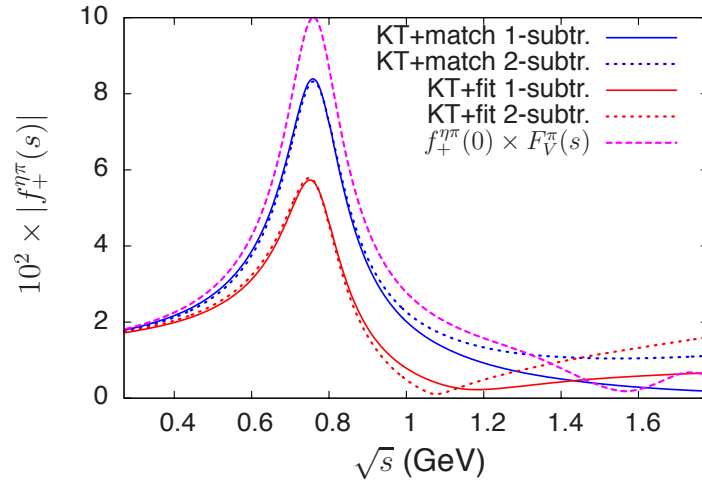


Figure 2: Vector  $\eta - \pi$  form factor computed from eq. (2) and different sets of  $\eta \rightarrow 3\pi$  Khuri-Treiman solutions and compared to a naive VMD shape.

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## 2.11 Effective Field Theories for Vector Particles and Constraint Analysis

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The strong interaction is described by quantum chromodynamics (QCD), a gauge theory with quarks and gluons as the fundamental particles. However, experimentally one observes baryons and mesons as bound states which can be arranged in representations of the flavor symmetry group  $SU(3)$ . If one assumes Lorentz invariance and the cluster decomposition principle, one can formulate an effective theory for the strong interaction in the low-energy regime by using the most general Lagrangian consistent with the assumed symmetries [1]. This concept is well-established as chiral perturbation theory for the quasi-Goldstone bosons, namely, pions, kaons and etas. In order to extend its applicability to higher energies, vector mesons such as the rho meson triplet should be included.

Since effective Lagrangians for vector particles (spin  $S = 1$ , parity  $P = -1$ ) are constructed with Lorentz four-vectors  $V^\mu$  or anti-symmetric tensors  $W^{\mu\nu} = -W^{\nu\mu}$  with four and six independent fields, respectively, one inevitably introduces more degrees of freedom than physically realized for a massive spin-one particle, which are  $2S + 1 = 3$ . Hence, suitable constraints are needed to eliminate the unphysical degrees of freedom in order to obtain a consistent theory already on a classical level. Typically, this leads to conditions for the numerous coupling constants in the Lagrangians, which can be helpful in the determination of those a-priori unknown low-energy constants using experimental data.

In the following, the results of such a constraint analysis are presented for two examples. It is a short summary of the diploma thesis by the first author, see chapters 4 to 6 in Ref. [2]. The mathematically precise description can be found in Ref. [3].

The first example is an effective theory for eight vector particles, assuming a *global*  $SU(3)$  symmetry. The Lagrangian reads

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^a V^{a\mu\nu} + \frac{M^2}{2}V_\mu^a V^{a\mu} - g^{abc}V_\mu^a V_\nu^b \partial^\mu V^{c\nu} - h^{abcd}V_\mu^a V_\nu^b V^{c\mu} V^{d\nu},$$

where  $V_{\mu\nu}^a = \partial_\mu V_\nu^a - \partial_\nu V_\mu^a$  and the indices  $a, b, c, d$  range from 1 to 8. Owing to the assumed  $SU(3)$  symmetry, the Lagrangian can be parametrized with five real couplings as follows,

$$g^{abc} = \gamma_1 f^{abc} + \gamma_2 d^{abc}, \quad h^{abcd} = \eta_1 \delta^{ac} \delta^{bd} + \eta_2 \delta^{ab} \delta^{cd} + \eta_3 f^{abe} f^{cde}, \quad (3)$$

where  $f_{abc} = \frac{1}{4i} \text{Tr}([\lambda_a, \lambda_b] \lambda_c)$  and  $d_{abc} = \frac{1}{4} \text{Tr}(\{\lambda_a, \lambda_b\} \lambda_c)$  with the Gell-Mann matrices  $\lambda_a$ . If one requires (1) that the number of constraints reduces the degrees of freedom to the physical number, and (2) that those constraints are conserved in time on a classical level, then the following conditions must hold,

$$\gamma_2 = 0 \quad \text{and} \quad \eta_1 = -\eta_2. \quad (4)$$

Next, this result from the constraint analysis can be used in a subsequent renormalizability analysis. It requires that the infinite parts resulting from one-loop contributions can be absorbed in the bare parameters of the Lagrangian, i. e. into the vertices at tree level, which is a necessary but not sufficient condition for a physically meaningful theory. Since

$$h^{1111} \stackrel{(3)}{=} \eta_1 + \eta_2 \stackrel{(4)}{=} 0,$$

the infinite parts of the one-loop contribution to the vertex  $V^1 V^1 V^1 V^1$  must vanish, so

$$0 = 9\left(\gamma_1^2 - 4\eta_3 - \frac{16}{3}\eta_1\right)^2 + 192\eta_1^2 \quad \Leftrightarrow \quad \eta_1 = 0, \quad \gamma_1^2 = 4\eta_3.$$

Finally, a massive Yang-Mills theory is obtained with one parameter  $\gamma_1$ . This result is similar to Ref. [4], where the same argument leads from a theory with three vector fields and a global U(1) symmetry to a massive Yang-Mills theory.

The second example uses anti-symmetric tensor fields  $W^{\mu\nu} = -W^{\nu\mu}$  to describe three massive vector particles. The Lagrangian reads

$$\begin{aligned} \mathcal{L} = & -\frac{1}{2}\partial^\mu W^a_{\mu\nu}\partial_\rho W^{a\rho\nu} + \frac{M_a^2}{4}W^{a\mu\nu}W^a_{\mu\nu} - g^{abc}W^a_{\mu\nu}W^{b\mu\lambda}W^c_{\lambda}{}^\nu \\ & - h_1^{abcd}W^{a\alpha\beta}W^{b\gamma\delta}W^c_{\alpha\beta}W^d_{\gamma\delta} - h_2^{abcd}W^{a\alpha\beta}W^{b\gamma\delta}W^c_{\alpha\gamma}W^d_{\beta\delta}, \end{aligned} \quad (5)$$

where  $M_1 = M_2 = M$  and identical Lorentz structures resulting from two Levi-Civita tensors  $\epsilon^{\alpha\beta\gamma\delta}$  are omitted. Assuming U(1) invariance, the couplings can be parametrized using  $1 + 10 = 11$  real couplings,

$$\begin{aligned} g^{123} &= g_1, \quad h_1^{1111} = h_1^{2222} = d_1, \quad h_1^{3333} = d_5, \quad h_2^{1212} = -4(2d_2 + d_7), \\ h_1^{1122} &= 2(d_1 - d_2), \quad h_2^{1111} = h_2^{2222} = 2(d_6 - d_1), \quad h_1^{1212} = 2d_2, \quad h_2^{3333} = 2(d_{10} - d_5), \\ h_1^{1133} &= h_1^{2233} = d_3, \quad h_2^{1133} = h_2^{2233} = -2(d_3 - d_4 + d_8 + d_9), \\ h_2^{1313} &= h_2^{2323} = 2(d_9 - 2d_4), \quad h_1^{1313} = h_1^{2323} = d_4, \quad h_2^{1122} = 4(2d_2 - d_1 + d_6 + d_7), \end{aligned}$$

all other coupling are set to zero without loss of generality. The constraint analysis yields  $g_1 = 0$ , i. e. the three-vertex vanishes completely, and  $d_6 = d_7 = d_8 = d_9 = d_{10} = 0$ . Again, the subsequent renormalizability analysis uses those results and yields  $d_5 = d_4 = d_3 = d_2 = d_1 = 0$ . In summary, all interaction terms must vanish in Eq. (5), if one requires U(1) invariance, self-consistency with respect to constraints, and renormalizability. This result is completely different from the one using the vector formalism, and one should investigate tensor models including interactions with derivatives. However, such an extended analysis certainly needs computer assistance and smarter implementations, but it may yield valuable conditions for the numerous coupling constants in effective Lagrangians.

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## 2.12 Pseudoscalar-vector and vector-vector interaction and resonances generated

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The local hidden gauge approach [1] provides an extension of the chiral Lagrangians, including the interaction of vector mesons among themselves and with pseudoscalars and baryons. It has been used with success to study the interaction of vector mesons in [2, 3], where many resonances are dynamically generated as a consequence of this interaction. The picture offers also a good interpretation for the radiative decays of resonances into  $\gamma\gamma$  and other decay channels [4]. In the baryon sector it also gives rise to many baryonic resonances [5, 6, 7, 8].

One of the surprises was the realization that there are two  $K_1(1270)$  resonances, separated by about 100 MeV [9] and experimental evidence was found in [10].

Very recently we have shown [11] that an  $h_1$  resonance predicted around 1800 MeV in [3] has found experimental support from a BES experiment [12]. Similarly we have also shown [13] that one can explain within this picture the decays of  $J/\psi$  into  $\omega(\phi)$  and the resonances which are made up of two vectors in [3]. Also the decay of  $J/\psi$  into a photon and one of these resonances is well described in [14]. The same occurs with the decays of the excited states of  $J/\psi$  or of the  $\Upsilon$  [15].

The local hidden gauge approach has also allowed us to give a different interpretation of the peak seen in the threshold of the  $\omega\phi$  mass distribution in [16], which was interpreted there as a new resonance but shown in [17] to be a consequence of the  $f_0(17100)$  resonance.

The approach has proved very solid and highly predictive. It has also been extended to the charm and beauty sector where some experimental data are well reproduced and the approach leads to predictions of many new resonances [18, 19, 20, 21].

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## 2.13 Review of the $f_0(500)$ properties and its non-ordinary nature from its Regge trajectory

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In this talk I first reviewed the recent major revision of the  $f_0(500)$  resonance properties in the Particle Data Tables (PDT) [1], and the main results that have driven this change. After some brief introduction to the history of this controversial state, which is also known as the  $\sigma$  meson, I explained how the combination of new data with rigorous and model independent approaches has provided very convincing evidence of the existence and properties of this state, which was well known for practitioners within the “scalar meson community”, but has only made it very recently to the PDT, whose approach is more consensual and conservative. For a recent minireview, see [2]

An example of the precision attained with dispersive studies is given in Fig.3, taken from [3], where a constrained fit to data was performed. Later on, the dispersion relations are used to obtain the correct analytic continuation to the complex plane in a model independent way, and determine the position and residue of the resonance associated pole.

As a result of this kind of analyses the 2012 PDT has finally reduced the quoted uncertainties of the  $\sigma$  mass, by a factor of more than five, down to 400 to 550 MeV, and width, by a factor of two, now estimated between 400 and 700 MeV. This new uncertainty estimate is shown in Fig.4, as a dark gray area, versus the old one, represented as a large light gray rectangular area, which was quoted from the 2002 edition until 2010, despite considering the  $\sigma$  meson as a “well established state”. To my view, these RPP criteria are still rather conservative, and for the  $\sigma$  I would only rely on pole extractions based on rigorous analytic methods. Furthermore, the PDT ‘Note on light scalars’ suggests that one could “take the more radical point of view and just average the most advanced dispersive analyses” (here correspond to [5, 6, 7, 8], shown in Fig.4), to find:  $\sqrt{s_\sigma} = (446 \pm 6) - (276 \pm 5)$  MeV.

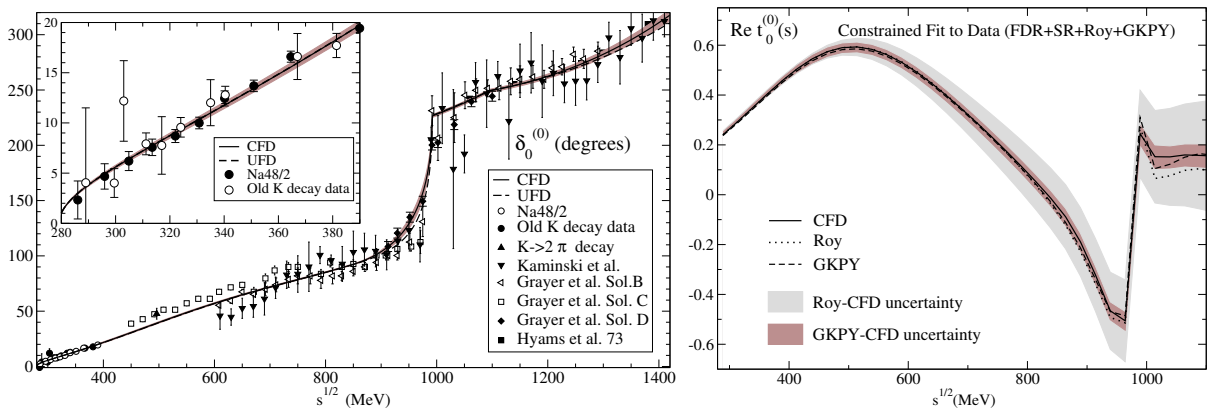


Figure 3: Scalar-isoscalar  $\pi\pi$  scattering figures from [3]. Left: Data on the  $\delta_0^{(0)}$  scattering phase versus the dispersive parameterization. Right: Fulfillment of Roy and GKPY equations for this same wave.

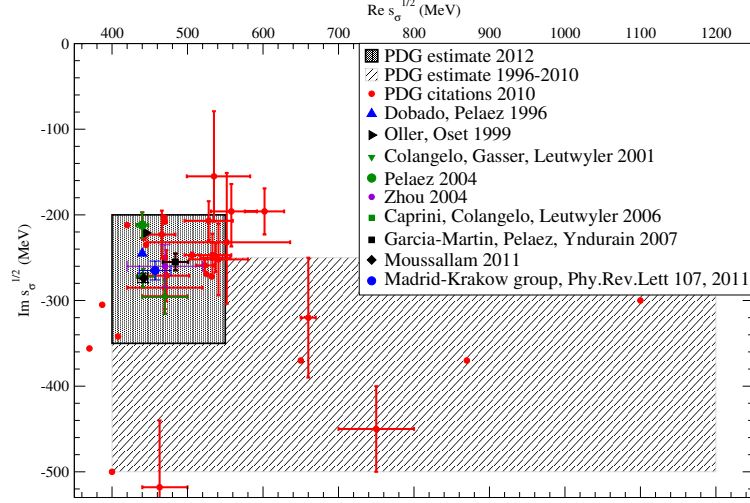


Figure 4:  $f_0(500)$  poles in the PDT[1]. Non-red poles are obtained from dispersive or analytic approaches [4, 5, 6, 7, 8].

In this talk I also reported on our recent calculation [9] of the Regge trajectory of the  $f_0(500)$  meson within a dispersive analysis that allows us to deal with the widths of the resonances. Our only input is the position and residue of the pole that dominates a given elastic partial wave in two body scattering. When applied to pions, we obtain an almost real and linear trajectory for the  $\rho(770)$  whose intercept and slope is in good agreement with the well known linear trajectories for ordinary hadrons whose slope is universal and  $O(1\text{GeV})$ . Note that the linear trajectory is not an input, but a result. In contrast, when the same method is applied to the  $f_0(500)$  we find a non-real, non-linear trajectory, whose slope at  $s = 0$  is about two orders of magnitude smaller than the ordinary trajectories. This is a strong hint on the non  $q\bar{q}$  nature of the  $f_0(500)$  resonance.

I thank the organizers for their kind hospitality and the nice workshop organization.

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## 2.14 Pole Identification with Laurent + Pietarinen Expansion in Meson Physics

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We present a new approach to quantifying pole parameters of single-channel processes based on a Laurent expansion of partial-wave T-matrices in the vicinity of the real axis [1]. Instead of using the conventional power-series description of the non-singular part of the Laurent expansion, we represent this part by a convergent series of Pietarinen functions. As the analytic structure of the non-singular part is usually very well known (physical cuts with branch points at inelastic thresholds, and unphysical cuts in the negative energy plane), we find that one Pietarinen series per cut represents the analytic structure fairly reliably. The number of terms in each Pietarinen series is determined by the quality of the fit. The method is tested in two ways: on a toy model constructed from two known poles, various background terms, and two physical cuts, and on several sets of realistic  $\pi N$  elastic energy-dependent partial-wave amplitudes (GWU/SAID - [2, 3], and Dubna-Mainz-Taipei - [4, 5]). We show that the method is robust and confident using up to three Pietarinen series, and is particularly convenient in fits to amplitudes, such as single-energy solutions, coming more directly from experiment; cases where the analytic structure of the regular part is a-priori unknown.

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## 2.15 Light Meson Physics with Crystal Ball at MAMI

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The A2 collaboration at the Institute for Nuclear Physics in Mainz, Germany, carries out experiments with Bremsstrahlung photons derived from electrons in the Glasgow-tagging spectrometer [1]. The electrons are accelerated in the Mainz Microtron (MAMI) [2, 3] up to a maximum energy of  $E_e = 1604$  MeV. With the Crystal Ball-spectrometer [4] and a forward spectrometer-wall consisting of TAPS-crystals [5] the A2 collaboration performs studies of light meson decays.

Results from the A2 collaboration include the most precise  $\eta$  and  $\eta'$  photoproduction cross sections to date. The results for the  $\eta$  meson cover a wide range from threshold to  $\sqrt{s} \approx 1.9$  GeV [6]. In the case of the  $\eta'$  only a limited range can be covered due to the maximum electron energy from MAMI. Nevertheless, a preliminary analysis of the data taken by the A2 collaboration shows unprecedented accuracy in the threshold region.

The A2 collaboration has also studied low-energy QCD in particular  $\chi$ PT related decays. The isospin-breaking  $\eta \rightarrow 3\pi^0$ , which can be related to the up- and down-quark mass difference, was measured with the worlds best accuracy [7, 8]. The amplitude of the  $\eta \rightarrow \pi^0\gamma\gamma$  decay has first sizable contributions at  $O(p^6)$ , but the low-energy constants have to be determined from models. Thus, this decay is a stringent test of  $\chi$ PT at next-to-next-to leading order and also of these models. A soon to be published analysis of this decay gave  $1.2 \cdot 10^3$   $\eta \rightarrow \pi^0\gamma\gamma$  events which is currently the most accurate result, but for distinguishing between different models even higher precision has to be reached. The preliminary decay width  $\Gamma(\eta \rightarrow \pi^0\gamma\gamma) = (0.33 \pm 0.03_{\text{tot}})$  eV agrees with all theoretical calculations but disagrees with the competitive preliminary result from the KLOE experiment by more than four standard deviations.

The A2 collaboration also contributes to the studies of transition form factors which do not only probe the structure of these particles but might also be of importance for Standard Model calculations of the light-by-light contribution to the Anomalous Magnetic Moment of the Muon. In 2011, the determination of the  $\eta$  transition form factor based on  $\sim 1350$   $\eta \rightarrow e^+e^-\gamma$  events [9] was published. An independent analysis of 3 times more data gave roughly 20,000  $\eta \rightarrow e^+e^-\gamma$  events. The resulting transition form factor agrees very well with all earlier measurements. Though the result shows good agreement with theoretical calculations the statistical accuracy does not allow for ruling out any prediction. The new result of the A2 collaboration will be published soon.

Breaking of  $C$ -violation was studied through measuring the branching ratios for the  $\omega \rightarrow \eta\pi^0$ ,  $\omega \rightarrow 2\pi^0$  and  $\omega \rightarrow 3\pi^0$  decays [10]. The upper limits determined by the A2 collaboration are to date the only values used by the PDG [11].

In the next few years the A2 collaboration plans to continue studying the topics mentioned above. The statistics on already analysed decays will be improved greatly. The  $\eta/\eta' \rightarrow 3\pi^0$  and  $\eta' \rightarrow \eta\pi^0\pi^0$  decays will be studied as well as pseudoscalar-vector- $\gamma$  tran-

sitions like  $\eta' \rightarrow \omega\gamma$  and  $\omega \rightarrow \eta\gamma$ . Furthermore, it is planned to investigate transition form factors in  $\pi^0/\eta/\eta' \rightarrow e^+e^-\gamma$  and  $\omega \rightarrow \pi^0 e^+e^-$  decays.  $C$ - and  $CP$ -violation will be examined in  $\pi^0/\eta \rightarrow 3\gamma$ ,  $\eta \rightarrow 2\pi^0\gamma$ ,  $\eta \rightarrow 3\pi^0\gamma$  and  $\eta \rightarrow 4\pi^0$  decays. As background for the  $\pi^0 \rightarrow 3\gamma$  decay the allowed  $\pi^0 \rightarrow 4\gamma$  might be studied which has never been seen yet, but some hadronic models predict a branching ratio within the reach of the Crystal Ball at MAMI experiment.

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## 2.16 Measurements of Kaon Decays

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The NA48 and NA62 experiments at CERN have a long tradition of kaon decay studies. NA48 as successor of NA31 started measuring direct CP violation in  $K^0$  decays in 1997, followed by NA48/1 in 2002 (rare  $K_S$  and hyperon decays) and NA48/2 in 2003 and 2004 ( $K^\pm$  decays). In the year 2007, still with the original NA48 detector, a long data-taking period was performed by the already formed NA62 collaboration for the precise measurement of the ratio  $R_K = \Gamma(K \rightarrow e\nu)/\Gamma(K \rightarrow \mu\nu)$ .

Here we report on recent measurements of NA48/2 and NA62 ( $R_K$  phase) on rare kaon decays and on prospects for the future NA62 experiment, which starts data-taking with a new detector at the end of 2014.

**Precise Measurement of  $K^\pm \rightarrow \pi^\pm \gamma \gamma$**  The amplitudes of  $K \rightarrow \pi \gamma \gamma$  decays have no contributions of  $\mathcal{O}(p^2)$  in Chiral Perturbation Theory (ChPT). Moreover, at  $\mathcal{O}(p^4)$  only two-pion loop diagrams contribute, resulting in a Wigner-cusp at  $2m_{\pi^+}$  in the  $\gamma\gamma$  invariant mass. For the charged decay  $K^\pm \rightarrow \pi^\pm \gamma \gamma$ , the  $\mathcal{O}(p^4)$  amplitude depends on only one free parameter  $\hat{c}$  which should be of  $\mathcal{O}(1)$  [1]. At the following  $\mathcal{O}(p^6)$  additional contributions as unitarity corrections and pole contributions have to be taken into account [2], resulting e.g. in a non-zero rate at  $z = 0$  as shown in Fig. 5 (left).

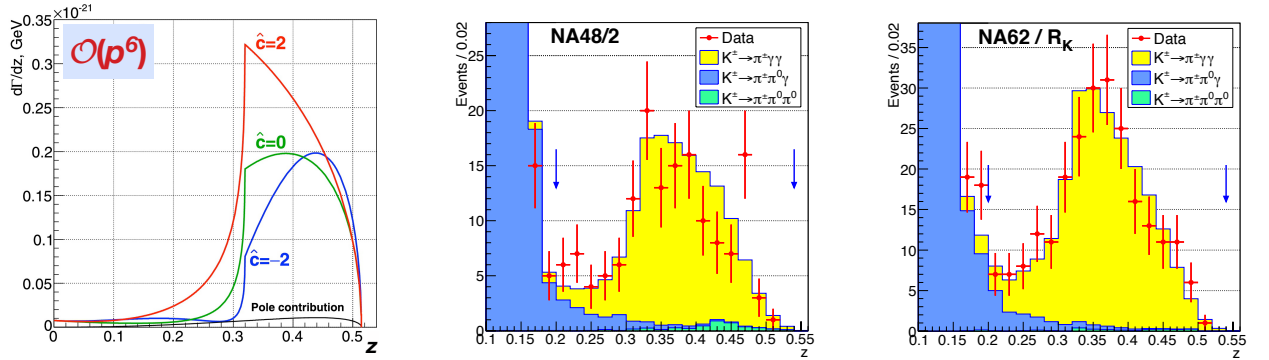


Figure 5: Distributions of  $z = m_{\gamma\gamma}^2/m_K^2$  for  $\mathcal{O}(p^6)$  ChPT (left) and NA48/2 [3] (center) and NA62/ $R_K$ -phase data [3] (right). The arrows indicate the region used for the  $\hat{c}$  extraction.

Both NA48/2 and NA62 have collected comparable data samples of  $K^\pm \rightarrow \pi^\pm \gamma \gamma$  decays, resulting in a total of 324 candidates with an expected background of  $27.9 \pm 1.3$  events from  $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$  and  $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$  decays. For both data sets separate analyses were undertaken [3, 4]. Combining both measurements yields (in  $\mathcal{O}(p^6)$  ChPT) a value of  $\hat{c} = 2.00 \pm 0.26$ , where the uncertainty is dominated by the data statistics.

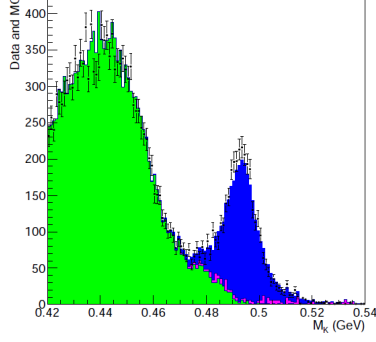


Figure 6:  $K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-$  signal (blue) for  $\approx 40\%$  of the NA48/2 data (in green:  $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ ) [6].

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ (signal)	45 events/year
$K^+ \rightarrow \pi^+ \pi^0$	5
$K^+ \rightarrow \mu^+ \nu$	1
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	<1
3 tracks	<1
$K^+ \rightarrow \pi^+ \pi^0 \gamma$	1.5
$K^+ \rightarrow \mu^+ \nu \gamma$	0.5
others	negligible
<b>Expected bkg</b>	<b>&lt;10</b>

Figure 7: NA62 expectations for  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  SM-events and background for one year of data-taking [7].

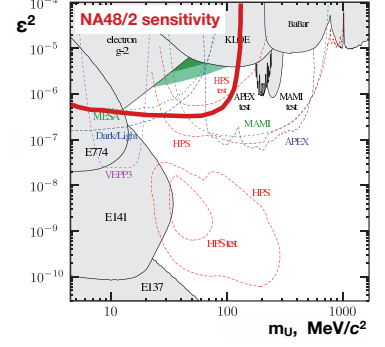


Figure 8: Various exclusion limits for the  $U$  boson [8]. The sensitivity of NA48/2 is indicated in red [7].

**First Observation of  $K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-$**  The decay  $K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-$  is similar to  $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$  with an internal photon conversion. It is dominated by inner bremsstrahlung (IB) while direct photon emission (DE) is a sub-leading effect of  $\mathcal{O}(p^4)$  ChPT [5].

Using about 40% of their recorded data, NA48/2 has now reported the first observation of the decay  $K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-$  with about 2500 signal candidates and an estimated background of 280 events (Fig. 6) [6]. The analysis of the data is on-going.

**Future Reach for rare Kaon Decays** The aim of the new NA62 experiment is the measurement of about 100 Standard Model (SM) events of the decay  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  in two years of data taking (Fig. 7). With this statistical precision a huge amount of possible New Physics scenarios can either be found or ruled out.

In addition, the expected unprecedented statistics on  $K^+$  decays will allow to search for a variety of rare, forbidden, and non-SM  $K^+$  decays. An example is the search of the so-called dark photon or  $U$  boson, where already the on-going analysis of NA48/2 data will significantly improve the existing limits (see Fig. 8) [7].

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## 2.17 Meson Production and Decays with WASA-at-COSY

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New results have been obtained with the WASA detector at COSY on the light meson decays  $\pi^0 \rightarrow e^+e^-\gamma$  and  $\eta \rightarrow \pi^+\pi^-\pi^0$  as well as on elastic neutron proton scattering in the energy range of a narrow resonance-like structure observed in double pionic fusion reactions.

Speculatively, recent unanticipated astrophysical observations (for refs. see e. g. [1, 2]) might be explained by a dark matter WIMP from a secluded gauge sector under which SM particles are uncharged (see [3] for a review, and [4] for early incarnations of the concept of a new light boson). In one scenario, the coupling to the SM arises from the kinetic mixing of the gauge boson (with a mass at the GeV scale) of a dark  $U(1)_d$  with the SM  $U(1)$ , with the mixing parameter  $\epsilon$  expected of the order of  $10^{-4} - 10^{-2}$ . Due to its small width the  $U$  boson or *dark photon* should be observable as a narrow peak in the lepton-antilepton invariant mass in light meson conversion decays. Search channels include  $\phi \rightarrow \eta U$ ,  $\eta \rightarrow \gamma U$ , and  $\pi^0 \rightarrow \gamma U$  with  $U \rightarrow e^+e^-$ . New results from WASA-at-COSY on the decay  $\pi^0 \rightarrow \gamma e^+e^-$  [2] constrain the parameter space for  $U$  boson masses  $20 \text{ MeV} \leq m(U) \leq 100 \text{ MeV}$  and mixing parameter values around  $2 - 3 \cdot 10^{-3}$  further compared to previous results in this range by SINDRUM [5] and KLOE [1]. An intriguing motivation to study particularly this part of the parameter space is the possible  $U(1)_d$  contribution to the anomalous magnetic moment of the muon. To get agreement between theory and experiment for the muon anomaly within two standard deviations defines a *welcome band* [6]. For the mass range given above, we expect the full WASA-at-COSY statistics, which is at least an order of magnitude larger, to cover this band completely.

The decays  $\eta \rightarrow 3\pi$  proceed via isospin symmetry breaking in the strong interaction, and electromagnetic corrections are expected to be small [7]. A precision determination of the light quark mass difference requires an accurate theoretical calculation, reproducing the dynamics of the  $3\pi$  final state (see e. g. [8] and references therein). Theoretical predictions can be tested with precision data on the  $\eta \rightarrow 3\pi$  Dalitz plots. The largest statistics presently available are from the KLOE experiment with the final Dalitz plot containing  $1.3 \cdot 10^6$  events [9]. However, the parameters  $a$  and  $b$  in the obtained Dalitz plot parametrisation [9] are difficult to reproduce theoretically. An independent measurement has been done with WASA-at-COSY using the tagging reaction  $pd \rightarrow {}^3\text{He} \eta$  and a sample of  $1.7 \cdot 10^5$   $\eta \rightarrow \pi^+\pi^-\pi^0$  events. Within  $2\sigma$  the WASA-at-COSY values [10] confirm both the published KLOE data [9] as well as preliminary results on the full KLOE statistics. A significantly larger sample of  $\eta$  decays has been measured with the WASA detector in  $pp \rightarrow pp\eta$ , and statistics are expected to be comparable to the data from [9].

Recently, a narrow resonance-like structure has been observed in the elementary double pionic fusion reactions  $pn \rightarrow d\pi^0\pi^0$  and  $pn \rightarrow d\pi^+\pi^-$  [11]. With no conventional explanation at hand as of now, the signal is consistent with an s-channel resonance in the proton-neutron

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and  $\Delta$ - $\Delta$  systems with a mass of  $2380 \text{ MeV}/c^2$ , a width of  $\Gamma \approx 70 \text{ MeV}$  and quantum numbers  $I(J^P) = 0(3^+)$  favoured by the deuteron and pion angular distributions. Such a resonance must also be observable in elastic proton-neutron scattering, in particular in the analysing power  $A_y$  which is determined only by interference terms of the partial waves contributing. Since there have been no experimental data on the  $np$  analysing power in the energy range of the resonance so far, data have been taken with the WASA detector in the quasifree mode,  $\vec{d}p \rightarrow pn + p_{\text{spectator}}$ . Measured analysing powers have been included in the SAID database, and a new partial wave analysis has been performed, which shows a resonance pole in the coupled  ${}^3D_3 - {}^3G_3$  partial waves as expected from the resonant structure observed in the double pionic fusion reactions [12]. Such a resonance might be interpreted as a hidden-colour six-quark state, but is also reproduced in recent quark model calculations as well as using a purely hadronic model for pions, nucleons, and  $\Delta$ 's [13].

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